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Prediction of Energetic Particle Disturbances

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1 May 1981

Interim Report

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This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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An evaluation of the present status of capabilities to predict energetic radiation in space is presented. Recommendations to increase the accuracy of space radiation forecasting techniques are described.

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PREFACE

This working group report was prepared by G. A. Paulikas (Chairman), D. N. Baker, W. R. Barron, V. Domingo, P. R. Higbie W. L. Imhof, L. R. Lyons, R. L. McPherron, E. C. Roelof, M. Scholer, M. A. Shea, D. F. Smart, W. N. Spjeldvik, and J. I. Vette. The full membership of the working group is given below.

This report is a summary of the work of the Working Group on Energetic Particle Disturbance Predictions that was formed to participate in the International Solar-Terrestrial Predictions Workshop held in Boulder, Colorado in April 1979. This report will be published in Volume II of the Proceedings of the workshop along with group reports from the other thirteen working groups at the workshop. Review papers pertinent to the working group reports will accompany those reports in Volume II. Volume I is comprised of papers written by groups that routinely furnish predictions on the sun-earth system (solar activity, ionospheric condtions, etc.). A third volume will contain contributed papers and will appear substantially after the first two volumes. The Proceedings are being edited by Dr. Richard Donnelly of the NOAA Environmental Research Laboratories in Boulder and will be available in early 1980.

The working groups were:

A1 Long Term Solar Activity Predictions

A2 Short Term Solar Activity Predictions

B1 Interplanetary-Magnetosphere Interactions

B2 Geomagnetic Disturbance Prediction

B3 Energetic Particle Disturbance Prediction

C1 Magnetosphere-Ionosphere Interactions

C2 High Latitude E- and F-Region Ionospheric Predictions

C3 Midlatitude and Equatorial E- and F-Region Ionospheric Predictions

D Solar-Weather Predictions

E Communications Predictions

F Geomagnetic Applications

G Spacecraft Environment and Manned Spaceflight Applications

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PREDICTION OF ENERGETIC PARTICLE DISTURBANCES

1. INTRODUCTION

The Working Group on Energetic Particle Disturbance Prediction evaluated the present status of our capabilities to predict energetic particle disturbances in space and developed a series of findings and recommendations. These recommendations, if implemented, promise to significantly increase the accuracy of existing forecasting techniques for the prediction of solar particle fluxes near the earth and to allow the development of predictive techniques for forecasting magnetospheric particle disturbances - a field which, at the present time, totally lacks operational short term forecasting capability.

This report is structured to emphasize our findings and recommendations. The interested reader will find additional relevant background material in the Appendices attached to the Working Group report. We have also included a selected list of references, many of which can be found in these Proceedings. These references may illuminate various aspects of the state of the art of energetic particle disturbance predictions or serve as authoritive reviews of work in this field.

2. SCOPE

This report specifically addresses the prediction of fluxes of energetic particles in space. Necessarily, our interests overlap those of other Working Groups concerned with the predictions of solar, interplanetary and magnetospheric phenomena and the reader should consider our findings and recommendations in the context of the entire field of magnetospheric physics and solar flare predictions. We have chosen to limit the scope of our recommendations by, first, considering only how to predict energetic particle fluxes, be they of solar or magnetospheric origin. Second, we have limited our attention to those areas which are of major importance in a practical sense, i.e., where either operational prediction schemes exist (Avdyushin et al., 1979; Heckman, 1979) or seem to be highly desirable and where an improved predictive capability can be of significant benefit to solar-terrestrial physics as well as to applications-oriented users in society. Using these criteria as a filter, we chose to address in detail the problems of solar energetic particle prediction, the prediction of the properties of the particle populations generated by magnetospheric storms and substorms and the prediction of long-term variations in the populations of magnetospheric particles. Detailed findings and recommendations for each of the areas are given below.

The sections below summarize our findings and recommendations. The recommendations concerning prediction of solar particles were developed with a view of building on the base of the operational PPS-76 program described elsewhere in these Proceedings by Smart and Shea (1979). The recommendations concerning predictions of long term particle variations are a natural outgrowth of the work on magnetospheric particle population modeling reviewed by Vette et al. (1979) in these Proceedings. These references and the reports of

the other Working Groups on solar and magnetospheric predictions are a necessary (reading) precursor for the present report. We also recommend careful reading of the report prepared by the Working Group on spacecraft applications for the purpose of assessing such gaps as may presently exist between requirements for forecasts and the potential capabilities which exist and can provide quantitative forecasts of particle disturbances.

3. FINDINGS AND RECOMMENDATIONS

3.1 Solar Flare Particles

3.1.1. Warnings and Reaction-Mode Predictions

The short term warning mode - forecasting of the particle fluxes which may arrive at the earth from a flare before the flare occurs - requires the prediction of the gross optical, radio and X-ray emission characteristics of the flare. A lumped parameter, such as the "comprehensive flare index" (CFI) of Dodson and Hedeman (1971) might be used for a rather rough estimate of peak flux as well as the total > 10 MeV proton flux and relativistic electron fluxes in cases where coronal and interplanetary propagation are expected to be about average. If predictions of the probability of flare occurrences (e.g., in terms of the distribution of the CFI) can be made for the entire transit of an active region, or for several solar rotations then rough estimates of energetic particle fluxes could be attempted in the same way for a long-term warning mode. For predictions of particle fluences or other gross parameters describing solar particles over a complete solar cycle the best course would be to use retrospective data compilations covering the last two solar cycles (Modisette et al., 1965; King, 1974; Stassinopoulos and King, 1972) to estimate the likely course of particle emissions during future solar cycles.

The short-term reaction mode - forecasting the subsequent history of a particle event after the flare has occurred - reduces many of the ambiguities of the warning mode by estimating from real-time data:

(i) Particle energy spectrum and composition at the acceleration site

(ii) Spatial and temporal dependence of particle emission from the corona

(iii) Propagation from the corona to earth

We analyze these three elements of the short-term reaction mode in detail below, and then point out how some of the techniques can be applied to improving the short-term warning mode. The reader should note that a program called PPS-76, developed by Smart and Shea and described elsewhere in these Proceedings is in operational use and already incorporates some of the ideas which are suggested as requiring further development below. The present discussion builds on the experience and insight gained from developing and using PPS-76.

3.1.2. Spectrum and Composition

Currently the most reliable predictor of > 10 MeV proton fluxes (e.g., PCA events) is the flare radio burst spectral distribution at millimeter and centimeter wavelengths (Castelli and Guidice, 1976; Akin'yan et al., 1977a, 1979a, 1979b; Bezrchenkova et al., 1977). The predictions of proton intensities have been improved by incorporating rough parameters describing coronal propagation. The slope of the proton spectra can also be predicted with reasonable accuracy from radio observations (Bakshi and Barron, 1979a, b; Barron and Bakshi, 1979). There have been few attempts to predict the intensities and spectra of relativistic electrons since the relativistic electrons usually accompany protons > 10 MeV and their spectra are rather reproducible ($\frac{dN}{dE} \propto E^{-3}$). The prediction of relativistic ground level events (GLE) from flare diagnostics is less reliable than for subrelativistic energies.

Composition at high energies (e.g., the proton/helium ratio) is not too variable in large events, but the recently discovered low-energy (~ MeV/ nucleon) "Z-rich" events (Hovestadt et al., 1975; Anglin et al., 1977; Zwickl et al., 1978) are usually from small flares on the sun's western hemisphere and are consequently difficult to predict.

The use of satellite measurements of soft X-ray fluxes (~ 1-10A) for prediction have not been exploited to the extent that the radio observations have. However, the significant contribution of X-ray related indicators to the mix of parameters in the comprehensive flare index (CFI) of Dodson and Hedeman (1971) suggests that the soft X-ray signature may be a good candidate as an additional parameter which may improve our abilities to characterize the acceleration processes occurring in flares.

Recommendations

(i) Multi-frequency radio patrols (24 hour coverage) should be continued and the data fed to forecasters for the purpose of improving reaction mode prediction of flare proton intensities and spectra.

(ii) Satellite measurements of soft (~ 1-10A) solar X-rays should continue, and there should be further scientific investigation of the use of both soft and hard X-rays as proton and electron prediction parameters.

(iii) Optical flare patrols (24 hour coverage) should be continued as these still provide the basic alert for possible flare particle events.

3.1.3 Coronal Particle Emission

Findings

Although we do not know whether particle accumulation into coronal storage is impulsive or extended in duration, we do know from satellite and ground-based measurements of particle flux anisotropies that > 10 MeV protons and > 0.2 MeV electrons have been continuously released for as long

as a day after a large flare (Roelof and Krimigis, 1977). There is no known solar diagnostic of extended injection; the information regarding extended injection is inferred indirectly from the large outward field-aligned anisotropies of the particles observed in interplanetary space.

Once injected into the corona, high energy particles can cover virtually all longitudes in the corona, and the emission of protons and ions from the corona can be extremely heterogeneous. In the two largest flare proton events in the last solar cycle, multiple spacecraft observations using near-earth and Pioneer detectors revealed intensity differences in > 10 MeV protons of more than a factor of 100 across $> 50^{\circ}$ in longitude a day or more after the flare (Keath, et al., 1971; Roelof et al., 1974). Coronal magnetic structure must hold the key to this behavior. A coarse diagnostic of global coronal structure is the H_{α} Synoptic Chart (McIntosh, 1972; 1979) which delineates large-scale magnetic polarity boundaries, and has been applied with some success to particle event prediction (Gold and Roelof, 1976; Roelof et al., 1977; Akin'yan and Chertok, 1977; Akin'yan et al., 1977b). More detailed associations of coronal magnetic structures with particle transport have been made using potential-field calculations based on high resolution Kitt Peak magnetograms, but the most direct identifications are possible from emission loops visible in the soft X-ray (44-54 A) and EUV images obtained from Skylab and various rocket shots.

Although not yet fully scientifically validated, it appears that the non-homogeneous transport could result from the requirements that there be closed loops to move the accelerated particles across the corona, but that these particles must eventually find regions of predominantly open field lines in order to escape into the interplanetary medium. These open regions then would be the structures that modulate particle injection into interplanetary space as a function of solar longitude and latitude.

Recommendations

(i) Acquire one image per day of the sun in soft X-rays ($\sim$ 40A) or EUV with $\approx$ 5" resolution (sufficient to identify emission loops $\approx 0.2R_{\odot}$ above the photosphere). White light coronograph images are considerably less useful because they do not directly define structures on the disk without extensive and ambiguous deconvolution.

(ii) Continue of daily coverage of the sun with high resolution full disk magnetograms.

(iii) Develop daily "update" calculations of potential-field magnetic structure over limited or entire photosphere (the latter requiring the previous 27 days of observations for one global computation).

(iv) Continue scientific analysis of coronal particle transport. Paragraphs (i-iii) of this recommendation can be implemented to provide operationally useful data to forecasters.

3.1.4. Interplanetary Propagation

Findings

During the rising phase of most flare particle events, the flux of particles is anisotropic and field-aligned, indicating that particles faithfully follow (moving) interplanetary field lines (Roelof, 1979); this lack of cross-field scattering should also hold in the decay phase of the event (after coronal injection is essentially over), when the particles are being "convected" out of the inner heliosphere by the moving field lines (Zwickl and Roelof, 1979). Once the event maximum has been properly identified, the decay phase can be modeled rather accurately, as long as the field lines at earth have sampled a relatively homogeneous coronal injection history. This is often not the case because of strong injection gradients in the corona, so there may be abrupt rises or drops during the decay phase. There are also abrupt changes during the rise phase because our interplanetary field connection to the corona traverses the transition between regions with vastly different emission rates. Changes in the coronal connection cause the principal distortion in solar event histories.

Since the solar wind velocity structure controls the evolution of the large scale interplanetary field, it is fortunate that knowledge of the instantaneous solar wind velocity allows us to estimate the coronal connection point of the field line through the spacecraft at that time (Nolte and Roelof, 1973a, b). Real-time solar wind measurements therefore allow prediction (in the reaction mode) of abrupt discontinuities in particle fluxes. On the other hand, estimates of evolving solar wind structure would allow a warning mode prediction of abrupt flux changes. Such estimates could come from images of coronal structure (if the modulation is caused by a co-rotating stream) or estimates of the arrival of flare-generated plasma disturbances (which require theoretical calculations that realistically model the three-dimensional distortions of the interplanetary field).

The most promising, immediately available "remote sensing" techniques for the solar wind is the interplanetary scintillation (IPS) of galactic and extragalactic radio sources of small angular diameter (Watanabe, 1979). The main limitation of currently operating IPS arrays is the relatively small number of reliably scintillating sources (< 10) at observing frequencies > 70 MHz. Only a few of these sources lie in the ecliptic plane, so directional sensitivity to approaching solar wind disturbances has a seasonal dependence. Nonetheless, IPS measurements during some months provide unique and valuable information for warning mode predictions of strong distortions in particle event histories.

Recommendations

(i) Solar wind speed should be provided in real time for prediction of particle event histories in the reaction mode. The paper of Tsurutani and Baker (1979) in these *Proceedings* describes steps presently being taken to implement this recommendation.

(ii) Interplanetary scintillation multi-site observations of

solar wind speed should be obtained on a daily basis. Even though IPS directional sensitivity is seasonal, measurements during the optimal periods of the year are extremely valuable for predictions in the warning mode.

(iii) Research concerning three-dimensional distortion of the interplanetary field by solar flare plasma disturbances is essential to the understanding necessary for predicting the effect of these disturbances on energetic particle event histories.

3.2 Magnetic Storms

A magnetic storm is an interval of several hours to several days duration during which the horizontal component of the magnetic field at a near equatorial ground station undergoes a significant deviation from quiet values. A storm is characterized by the D_{st} index, which is an average over all local times of the deviations in H, and the asymmetry index, i.e., the range between maximum and minimum values of the deviation in H. These indices represent and are related to the currents of trapped particles circulating in the magnetosphere. The trapped particle populations in the entire outer magnetosphere undergo massive changes during and after magnetic storms with resulting ionospheric and aeronomic effects. The reader should consult the reports of the Working Groups on Interplanetary-Magnetosphere Interactions and Geomagnetic Disturbance Predictions to become more familiar with the phenomenology of magnetic storms and the report of the Working Groups dealing in ionospheric predictions and spacecraft applications to appreciate the effects.

There are two types of magnetic storms, those associated with solar flares and recurrent storms which are most probably associated with coronal holes. The geoefficiency of a flare depends on the location of the flare, its size and the direction of the photospheric magnetic field. Recurrent magnetic storms are more common near solar minimum. Their effectiveness in generating geomagnetic activity appears to be a consequence of an interaction between a high speed solar stream and slower plasma ahead of it (Mishin et al., 1979; Iyemori and Maeda, 1979). The interaction organizes the various plasma and field parameters in a systematic way. In particular, the interplanetary magnetic field (IMF) is tipped out of the ecliptic plane with a sudden transition from north to south, (or vice versa) occurring at the center of the interaction region.

Magnetic storms are controlled by the direction of the IMF and the solar wind velocity through the interplanetary electric field, $E_{sw} = -VB_s$ where B_s is equal to the GSM Z component of the IMF, if it is negative, and is zero otherwise. When the magnetosphere is treated as a linear system it is possible to predict a the D_{st} index as a function of time using an impulse response of roughly 10 hours duration convolved with E_{sw}. Thus, in principle, given the parameters of the interplanetary medium it is possible to predict D_{st}.

Recommendation

> We recommend that a workshop be organized to test and evaluate our ability to predict D_{st}. Data describing the state of the interplanetary medium would be used to predict D_{st} and then compared to D_{st} values calculated from ground observations.

Several processes are thought to be responsible for the injection and energization of ring current particles. A sudden enhancement of an azimuthal electric field will cause ambient particles drifting on closed paths inside the plasmapause to move inward. As they do this they gain energy and drift more rapidly creating an enhanced ring current (Lyons and Williams, 1979). Simultaneously particles at greater distances in the magnetotail drift earthward gaining energy and replacing those previously present and accelerated out of the region. Sporadically, substorms divert a portion of the tail current down magnetic field lines westward through the electrojet. This causes rapid increases in the magnetic field in a localized sector near midnight. This in turn creates an inductive electric field which accelerates particles through the betatron and drift-betatron processes. These particles rapidly drift out of the acceleration region becoming part of the source which supplies the inner magnetosphere (Clauer and McPherron, 1979).

Recommendation

> We recommend additional coordinated research or workshop-type activities which will better describe the quantitative relationship between D_{st}, or other magnetospheric parameters and indices, and the actual energy spectra and spatial distributions of the storm time ring current particle population.

The decay of the ring current is via wave particle interactions and charge exchange. When the IMF turns northward, the plasmapause begins to expand. As it expands, both the proton and electron distribution functions become cyclotron unstable producing waves which scatter particles into the loss cone thus precipitating the particles into the ionosphere.

The rate of precipitation of energetic electrons can be calculated from knowledge of the spectrum of plasmaspheric whistler-mode hiss (Speldvik and Lyons, 1979). Particles precipitated by this process penetrate to the D region of the ionosphere enhancing the ionization of this layer. This ionization alters atmospheric chemistry producing such effects as changes in the ozone content as well as effects on communications which can be quantitatively predicted.

The various physical processes linking a solar flare or coronal hole to eventual particle precipitation into the atmosphere are thought to be understood to varying degrees. By combining a variety of semiquantitative empirical relations and theoretical calculations, it should now be possible to crudely predict the magnetospheric effects of storms and the resultant atmospheric effects of particle precipitation during magnetic storms. An essential element for such predictions is measurement of the properties of the solar wind plasma and magnetic field immediately upstream of the earth's bow shock.

Recommendation

We recommend that a coordinated workshop be organized, involving magnetospheric and atmospheric scientists, for the purpose of assessing, using selected storm time data, the feasibility of predicting the beginning-to-end evolution of one or more magnetic storms, including aeronomic and ionospheric effects.

3.3 Substorms

At the present time it is difficult to agree on precise interpretations of all of the detailed features of magnetospheric substorms. However, associated with all significant substorm activity there are major changes in the near-earth magnetic field and there are also substantial re-distributions and energizations of particles in the outer magnetosphere. We conclude that major substorm effects involve a release of a large fraction of the energy which has been extracted from the solar wind and which has been stored within the magnetosphere. We adopt, therefore, the point of view that it is, and ought to be, of primary interest to users to define substorms in terms of the major substorm energy release in the form of charged particles. The reference substorm onset time (t=0) can be specified as the time of first appearance of intense fluxes of energetic magnetospheric particles near local midnight.

Warning Mode - Since we wish to predict substorm energetic particle disturbances, we presently recognize two powerful tools that are available for this purpose:

1) Measurement of the solar wind energy input function, $f(V_{sw}, B_z)$, to the magnetosphere.

   This basically involves some combination of the solar wind speed (V_{sw}) and the IMF north-south component (B_z). A measurement of $f(V_{sw}, B_z)$ can tell us the size of magnetospheric effects (substorms), but not when or where effects will occur. It seems possible that lead times of 30-60 minutes may be achieved if measurements were made at the sunward libration point (Tsurutani and Baker, 1979).

2) Measurements of the internal stresses of the magnetosphere.

   Such measurements can be made using energetic electron anisotropies and/or sensitive magnetometers at geostationary orbit (Baker et al., 1979a, b). This technique gives a fairly good indication (on a statistical basis) of when a substorm will occur. Substorm warnings one to two hours in advance of substorm onset times may be provided by the method.

   The size of the open field line region over the polar cap as determined by low altitude spacecraft or ground based magnetometers or radars is also a measure of the stress in the magnetosphere.

Recommendations

(i) Evaluate, in an operational sense, the efficacy of using the actual magnetospheric energy input function, $f(V_{sw}, B_z)$ as measured by ISEE-3 interplanetary data to compute the energy dumped by substorms using a suitable index.

(ii) Guided by result of the recommendation above, implement a real-time ISEE-3 data system. The paper by Tsurutani and Baker in these Proceedings provides a roadmap for acquiring the ISEE-3 data.

(iii) Develop a real-time system for utilization of geostationary energetic electron data for predicting substorm onsets and utilize the magnetometers presently in the geostationary orbit to aid in the measurements of magnetospheric stresses.

(iv) Using the appropriate data sets, study the details of magnetic field direction changes and electron drift-shell changes which might be used to estimate the size of the impending substorm disturbance.

Reaction Mode - Once a substorm has taken place, what can be done to update predictions or to specify the magnetospheric effects?

1) Magnetospheric effects (important for spacecraft charging or spacecraft operations):

   a) Plasma parameters can be measured directly by plasma analyzers or inferred by appropriate fitting techniques using data from more limited instrumentation.

   b) Radiation dose measurements can be made which are useful for assessing hazards to spacecraft operations.

2) Ionospheric and auroral effects (important for HF communications):

   a) Location and extent of auroral zone can be inferred from low altitude measurements of electron precipitation, or bremsstrahlung X-rays, or high altitude optical and X-ray imaging.

   b) Sensing of auroral zone precipitation from synchronous orbit observations may be possible for some applications through measurement of

      i) Strong pitch angle scattering

      ii) Prediction of drift trajectories in the magnetosphere using realistic models of the magnetosphere.

Recommendation

We recommend that research be undertaken to develop global models of the magnetospheric magnetic field fitted to real time measurements of magnetic field components (or the loss cone direction of energetic particle distributions) made by anumber of satellites. Encouragement should be given to develop instruments capable of imaging the auroral zone in UV or X-rays. Further effort should be devoted to study of parallel electric fields which considerably alter particle distribution functions at low altitudes and strongly affect auroral features; such efforts are clearly essential if low altitude effects are to be inferred from high altitude measurements.

Phenomena Not Predicted:

There are, obviously, many phenomena of interest to the scientific and application community, which we cannot predict. Several examples will suffice.

1) Ionospheric effects whose relationship to substorms is not clear or obvious. These include relativistic electron precipitation (REP) events and precipitation spikes observed by low altitude spacecraft.

2) $\frac{\partial B}{\partial t}$ during substorms (of interest for their inductive effects) except that magnitude of B is probably related to size of energy input $f(V_{sw}, B_z)$. Detailed knowledge of the substorm process and its triggering mechanism must be known before such estimates can be made.

Recommendation

Users should correlate times of observed effects in their systems with commonly used definitions of substorm onsets (particle injection times, mid-latitude positive bays in magnetograms) so that forecasters and scientists can know more precisely what is important to users. Publication of monitoring data might be of service in this regard.

3.4 Long Term Variations of Energetic Particles

In a predictive or warning mode, the long term averaged quantitative models of trapped protons and electrons described by Vette et al. (1979) in these Proceedings can be used to provide the fluences received by any spacecraft orbiting within the limits of the model. There is one region of space between L of 2 and 7 where predictions are not reproducible from year to year within acceptable accuracy. Solar proton fluence models consisting of event integrated fluences and statistics over the 20th solar cycle have been prepared and provide a good first-order estimate of the likely solar proton fluxes expected during the 21st cycle.

Recommendations

(i) Maintain quantitative trapped radiation electron and proton models to an accuracy of a factor of about 2 by incorporating new data at appropriate times.

(ii) Following the completion of the 21st solar cycle, compile the event integrated fluences and statistics for the solar proton events from 5 MeV up to the maximum energies observed and using riometer absorption events, recalibrate the 19th solar cycle compilations so that three cycles will be available to predict fluences in the 22nd cycle and beyond. The efforts to maintain a high accuracy historical record of galactic cosmic ray flux should continue.

(iii) Determine a representation of the electron fluxes that appear in the trapped region following a magnetic storm characterized by the D_{st} parameter and give its decay features over the whole region; this should be done in the frame work of a multi-storm sequence. In a reaction or specification mode there are several products that can be produced with existing data and the cause of the variability in multi-month flux averages over a portion of the outer zone can likely be determined.

(iv) On the basis of data collected over the 20th solar cycle, compile the statistics on storm injected electrons appropriate to planning a work schedule for man operating at the geostationary orbit for large facility construction and maintenance or repair of outer zone spacecraft by Shuttle visitation.

(v) Determine the cause of the time variations in outer zone electron fluxes characterized by other than the exponential decay, particularly those decays associated with flux increases produced by fast solar wind streams impacting the magnetosphere.

(vi) In order to speed up the pace of quantitative model development and to permit the experimenters to participate directly in this activity, use the newly developed coordinated data analysis workshop technique, in which computer interactive graphics is employed to manipulate and display a common data base constructed to address a specific problem.

4. SUMMARY OF RECOMMENDATIONS: WORKING GROUP ON ENERGETIC PARTICLE DISTURBANCES

Recommendation	Prediction	Status of Prediction Technique	Implications
Solar Particles			
Solar active region evolution (See Report of Working Groups on Solar Activity Prediction)			
Prediction of Particle Spectrum and Composition			
(i) Multi-frequency radio patrols	Proton intensity and spectrum	Operational	Operation of several ground stations
(ii) Soft (1-10A) solar x-ray measurement	Proton and electron prediction	Research	Satellite in orbit
(iii) Optical flare patrol	Particle flare occurrence	Operational	Operation of several observatories
Prediction of Coronal Transport			
(i) Soft x-rays (40 A) or EUV solar imaging 1/day	Coronal loop structure	Capability exists	Satellite in orbit
(ii) High resolution solar disk magnetograms	Magnetic field sector structure	Operational	Ground based observations
(iii) Daily calculation of potential field B structure over photosphere	Coronal loop structure	Research	Research
(iv) Research of coronal particle transport	2 Dimensional profile of particle flux release from the solar corona	Research	Research
Prediction of Interplanetary Transport			
(i) Solar wind speed in real time	Particle event development	Capability exists	Satellite in orbit
(ii) Multi-site interplanetary scintillations	Particle event development/prediction	Operational	Increase ground observations

(iii) 3-dimensional distortion of interplanetary magnetic field by solar activity	Effect of solar activity on particle flux profiles	Research	Research

<u>Magnetic Storms</u>

(See Reports of Working Groups on Interplanetary-Magnetosphere Interactions and Geomagnetic Disturbance Predictions)

Workshop to evaluate ability to predict D_{st} using interplanetary medium data	Prediction of magnetic storms	Research	Coordinated research
Research and relationship between D_{st} or other magnetospheric indices and the storm time ring currents	Prediction of particles in magneto-sphere during magnetic storms	Research	Coordinated research
Coordinated Workshop (involves magnetospheric and atmospheric scientist) to study the feasibility of predicting end-to-end evolution of one or more magnetic storms	Prediction of magnetic storm effects	Proposed	Coordinated research

<u>Magnetospheric Substorms</u>

Evaluation of magnetospheric input function with respect to the Solar wind-data provided by ISEE-3	Capability to predict substorm activity from solar wind data	Research	Research
Implement real-time ISEE-3 data system	Substorm activity/ warning 30-60 min	Capability exists	Data handling system
Develop real-time system for geostationary electron data prediction of substorm onset	Substorm activity/ warning 30 min	Capability exists	Data handling system
Research on predictive character-istics of B direction changes and electron drift-shell changes	Substorm activity/ warning 1-2 hours	Research	Research
Research to develop models of the magnetospheric B, Auroral zone UV and X-ray imaging, parallel electric field	Low altitude effects	Research	Instrumenta-tion for auroral zone X-ray and UV Imaging

User effects correlations to be done with substorm onsets	User effects prediction development	Proposed	Research
<u>Long term variations of energetic particles</u>			
Trapped radiation e and p models to be maintained	Particle fluxes in trapped radiation region	Operational	Data handling
Compilation of integrated fluxes of solar events (E_p > 5 MeV) and of galactic cosmic rays	Particle fluxes over polar caps and outside the magnetosphere	Operational	Data handling
Model of electron flux in trapped region following magnetic storm in function of D_{st}	Electron fluxes in outer radiation zone	Proposed	Research and data handling
Storm injected electrons in outer radiation zone:statistical compilation	Electron fluxes in geostationary orbit	Proposed	Research and data handling
Research on time variations of outer zone electron fluxes, associated with solar wind	Electron flux in outer zone	Research	Research
Coordinated data analysis workshops		Proposed	Coordinated research

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APPENDIX I

Short Term Magnetospheric Particle Variations (1 min < T < 1 day)

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Introduction

The interest in studying short term (1 min < T < 1 day) energetic magnetospheric particle variations stems from several sources, both scientific and applied. The scientific problems associated with this time domain include the entire substorm process as well as the coupling between the magnetosphere and interplanetary space (e.g., solar particle entry). The numerous practical problems which occur on the above timescales include spacecraft charging and radiation damage effects caused by solar proton events, communications interference from particle precipitation in the polar regions and even radiation hazards to people flying on great circle routes over the Arctic during solar proton events. Magnetospheric coupling to the atmosphere through precipitation of energetic particles gives rise to short term density disturbances in the thermosphere and is one link which has been suggested as joining the earth's weather and climate to solar activity. The ability to predict the occurrence, duration, evolution, and intensity of energetic particle flux variations in the magnetosphere is thus valuable both scientifically and for its contribution to practical human ventures.

Energetic Particle Processes

Figure 1 is a schematic representation of the generation and propagation processes for energetic particles of concern in solar-terrestrial predictions. The upper branch of the figure refers to particles energized at the sun by impulsive events such as flares. These particles travel through interplanetary space and eventually enter the Earth's magnetosphere and reach the atmosphere. The lower branch lists the processes by which particles are energized (0.01 - 5 MeV) in the earth's magnetosphere and then precipitate into the atmosphere or are otherwise lost from the magnetosphere. The processes listed in the lower branch include the substorm process which is still far from being completely understood. The reader should refer to the paper by Scholer in these Proceedings for a review of the solar particle entry process and to the reference in the reports of the Working Groups on Interplanetary-Magnetosphere Interactions and Geomagnetic Disturbance Predictions for additional insight into magnetospheric processes. Characteristic times are associated with various processes. Diamonds in the figure represent points at which one might break into the chain of events to make observations for predictive purposes.

The times that have been associated with the intermediate phenomena in the upper branch of Figure 1 are approximate characteristic times for 10 - 30 MeV/nucleon ions. For faster ions and for the electrons of interest, some of the quoted times are correspondingly shorter. We see that for any significant medium- and long-term forecast of solar energetic particle variations (> 1 day), only observations of the sun and the interplanetary medium for the purposes of predicting future particle emission and transport may be useful.

The reader should consult the reports of Working Groups on solar activity predictions to gain a perspective of the current status of our ability to predict solar activity both on the timescale of days as well as decades.

Magnetosphere Penetration

Once particles of solar origin have reached the neighborhood of the magnetosphere, where they may be detected by satellites, the particles will enter the different magnetospheric regions with little delay.

A review of experimental results on solar particle penetration into the magnetosphere has been published by Paulikas (1974). The reader should also consult the paper by Scholer in these Proceedings for a more recent review. The major points of these reviews are:

- solar electrons have immediate (within seconds) access to the magnetotail and polar caps;
- protons of E > 1 MeV have access to the low latitude boundary of the polar cap (that coincides more or less with the auroral region) in a very short time (in general, minutes) after reaching the magnetosheath. On the other hand the population of the tail lobes seems to suffer delays of the order of tens of minutes.
- Lower latitudes, within closed magnetic field lines, are penetrated when the geomagnetic activity is high. The same is true for geosynchronous orbit in the case of low energy protons. Higher energy protons (E_p > 20 MeV) reach the geosynchronous orbit at all times.
- The precipitation of protons of 1 MeV up to at least 300 MeV near the centers of the polar caps is subject to delays that vary between some minutes and several hours. The amount of delay depends on the orientation of the interplanetary magnetic field, while the flux intensities reached over the polar caps are dependent on the anisotropy of the interplanetary flux.
- Observations made by HEOS-2 in the high latitude magnetosphere show that the behavior of particles observed in the polar cap is the same as for those observed in the deep tail. Particle fluxes in the regions near the magnetopause and the neutral sheet are seen to closely follow the interplanetary proton flux; fluxes at the center of the tail lobe, on the other hand, follow interplanetary levels only after some delay.

Local Production of Energetic Particles

The ultimate energy source for locally energized particles in the Earth's magnetosphere is again the sun although particles originating in the earth's ionosphere may play a very significant role in magnetospheric dynamics. The Earth's ionosphere forms a complex lower boundary for the magnetosphere and there is strong evidence that part of the plasma in the magnetosphere is supplied by the ionosphere.

Coronal holes are the source of high speed solar wind streams. The persistence of coronal holes and magnetic field structure on the sun provide a recurrent pattern of high speed streams and magnetic sectors every twenty-seven days. Various structures in the solar wind including flare-produced shocks are propagated to the earth in two to five days. These structures evolve during the process of propagation and by the time the structures reach the distance of Jupiter's orbit, shock structures form due to the interaction of the high speed streams with more slowly moving solar wind particles. The closure of forward and reverse shocks from successive shock pairs results in a corotating cavity centered on the sun. The existence of such a cavity reinforces possible twenty-seven day periodicities. Thus, or^ crude prediction applicable to magnetospheric phenomena is the persistence of twenty-seven day patterns in energetic particle behavior.

The solar wind impinging on the Earth's dipole distorts the field and confines it to form the magnetosphere and the magnetopause boundary. Waves generated in this process act upon the incoming plasma to form a stand-off shock in the solar wind. These macroscopic structures are the average effect of microscopic processes. The solar wind parameters (de-.sity, temperature, bulk velocity, frozen-in interplanetary magnetic field) are functions of position and time. For example, standard deviations in the hourly averaged IMF magnitude can be comparable to the average itself. Furthermore, on occasions the IMF may not be uniform across scale lengths of the order of the magnetosphere. The actual dynamical processes at the magnetopause - dayside merging, plasma entry - and the exact morphology of the magnetopause are topics of active current research.

Despite the considerable uncertainties involved, it is clear that the coupling between the solar wind and the magnetosphere results in the transfer and storage of energy in the Earth's magnetosphere. It is thought that this storage is in the form of reconfiguration of the Earth's magnetotail. Indeed, inflation of the magnetotail is often observed before substorm onsets. Interplanetary shocks can cause sudden compressions of the Earth's magnetosphere and can simultaneously excite or trigger substorm activity. In any event, energy can be stored in the Earth's magnetosphere and then be released later in a sudden manner.

Whereas the initial storage of energy may take place over many hours; and in fact apparently does so continuously albeit with varying efficiencies, the consequent energy dissipation in substorms takes place on time scales of an half hour. During substorms particles can be accelerated to high energies - 10's of KeV to $\sim$ 1 MeV. These particles are injected into the outer radiation zones where they subsequently drift around the earth. The electrons and ions are pitch angle scattered and eventually precipitate into the Earth's atmosphere causing various changes to the ionosphere which are of practical importance as noted in the Introduction.

Particle Precipitation at Low and Mid Latitudes

Ion precipitation at low latitudes has been observed to yield ionospheric effects. Qualitatively this may be understood in terms of charge exchange of ring current ions. As these ions become neutralized some disappear out into space and some precipitate into the near equatorial atmosphere. When they

encounter the upper atmosphere these energetic neutrals can become reionized and form a temporary low altitude trapped radiation zone from which further atmospheric interactions take place.

At low mid latitudes significant fluxes of energetic electrons are almost continually precipitating into the atmosphere as evidenced by the regular observation of quasi-trapped electrons at low altitudes and at longitudes where the minimum longitude drift altitudes are below the surface of the Earth. The precipitating fluxes at low latitudes are generally much lower than at high latitudes. Nonetheless, the fluxes can be detrimental to satellite missions and can interfere with communications.

Although middle latitude electron precipitation occurs most all of the time, large variations in flux are often observed from one spacecraft orbit to another. Thus substantial changes in the precipitation mechanism takes place on timescales shorter than $\approx$ 100 minutes. At the present these variations are only understood to a limited extent. Variations associatd with magnetic storms are understood in terms of enhancement in the ambient radiation belt flux levels and the intensification of the scattering plasmaspheric hiss responsible for the post-storm precipitation. During other geomagnetic conditions our current knowledge is more meager. Enhanced ion convection across the plasmapause is thought to excite hiss generation and consequently variations in energetic electron precipitation at middle lattitudes. Empirically, the precipitation fluxes show some increase with increasing Kp index, but this dependence is small in relation to the rather large spread in flux values observed.

Man-made VLF waves can propagate through the ionosphere and enter the radiation belt region. It has been suggested that these waves may be important in inducing energetic electron precipitation; but evidence in support of this has not yet demonstrated that this is a significant mechanism.

Our ability to predict short term variations in precipitating electron fluxes at times other than magnetic storm recovery is thus quite limited. Without a more complete understanding of the precipitation processes, most notably the generation of the scattering wave turbulence, the most appropriate approach to predicting short term variations may be to rely on the empirical finding that the total intensities of electrons precipitating from the slot region have significant correlation coefficients for separation times of 24 hours or less. Accordingly, without further research, only the persistence prediction appears useful: that the precipitating fluxes in the near future will be comparable to their present intensities.

Particle Precipitation at High Latitude

At high latitudes in the auroral zone/outer belt regions the fluxes of precipitating electrons are generally much greater than at lower latitudes and their morphology is more closely related to geomagnetic activity and to the occurrences of substorms. Since time delays (up to several hours) in the daytime precipitating fluxes may be associated with gradient drift, the known substorm morphology can presently provide a basis for predicting the fluxes of precipitating relativistic electrons in the dawn-noon time frame. The predictability of electron precipitation is complicated by the occurrences of

impulsive precipitation spikes at high latitudes, many of which occur in the midnight sector. To improve our predictive ability widespread precipitation patterns must be measured and for this purpose the satellite x-ray mapping technique can provide valuable data. With such a technique, from a polar orbiting satellite the spatial and temporal morphology can be studied in far more detail than has been heretofore possible.

Prediction Techniques

The diamonds in Figure 1 represent the points at which observations might be made for predictive purposes. We shall briefly mention the types of phenomena which can be observed and the techniques which might be used to make further predictions.

(A) Solar flares may be observed in optical, radio and X-rays. Using models of typical proton events (see review by Shea and Smart in these Proceedings), predictions can be made for the appearance and duration of solar particle events at Earth.

(B) Observations can be made of the fluxes of energetic particles by satellites in interplanetary space. Such observations can be used to update model predictions.

Observations of energetic particles by spacecraft in magnetospheric regions easily reached by these particles (e.g., geosynchronous for protons of energies > 20 MeV, electrons at the polar caps) can be used to predict entry of high energy protons into the tail lobes and precipitation onto the polar caps. Optical and X-ray imaging of the auroral region could be used to follow the course of a solar particle event as well as substorm evolution (cf. F and H below).

(C) Solar wind parameters (density, temperature, bulk velocity, components of the embedded magnetic field) can be measured upstream from the Earth. Various combinations of these parameters could be combined to give an empirical prediction of some index (e.g., Dst or AE) which is indicative of storm or substorm activity.

(D) Electron anisotropies obtained by spacecraft measurements near the geosynchronous orbit can indicate the occurrence of magnetic stresses in the magnetosphere. Direct observation of inflation of the magnetotail using magnetometer techniques can also indicate the existence of large amounts of stored energy in the magnetotail which might be released in the form of a substorm.

(E,F) Real time measurements of magnetic disturbances at ground stations can be used to track substorms. Particle injections can be observed by multiple spacecraft. Also multiple spacecraft observations of the magnetic field or symmetry axis for energetic electrons could be used to infer the parameters in a simple magnetic field model for the Earth's magnetospheric magnetic field. Theoretical solutions or computer modeling of the evolution of the observed particle distributions in the model magnetic field could be used to predict the motions of these particles and their eventual precipitation into the atmosphere.

(G) Spacecraft near geostationary orbit or in the geomagnetic tail can observe boundary motions or thinning on time scales of minutes prior to flux injections. For spacecraft in geostationary orbit, changes either in the gross counting rates due to the gradient in the flux profile or direct observations of the gradient for high energy proton fluxes (east-west effect) can be used to infer the inward convection of a boundary. The basic three-dimensional problem of thinning and the shape of the injection region must be understood in more detail. Local vs global effects must also be investigated.

(H) Direct observation of energetic flux levels and their pitch angle distribu tions can be used to predict precipitation of energetic electrons into the ionosphere. Coupled with particle trajectory calculations, these predictions might be extended to regions beyond the foot of the field line passing through the satellite.

Input from Other Working Groups

Much more research needs to be done into the substorm process to predict when and under what conditions we may expect energetic particles to be generated and to establish the connection between the magnitude of the generated fluxes and the state of the magnetosphere and the interplanetary medium. Theoretical studies should be carried out to describe the transport of injected particles in a realistic model of magnetic and electric fields. Much work has already been done using relatively crude field models for low energy plasma. Investigations should be directed towards simple magnetic field tail-like models which exhibit tail-like features and for electrons and ions with energies of less than 100 keV. Data comparisons should be made between magnetospheric particle observations and those data sets that bear on the coupling between the magnetosphere and the ionosphere and the upper atmosphere.

Testing and Evaluation of Predictions

There are at least four methods to test and evaluate prediction techniques. Table I lists pro's and con's for each of these methods. The methods are listed here as though they might be stages in the evaluation of a prediction technique.

(1) Traditional Collaborations. The traditional method for generating new scientific concepts and establishing new technologies is to form small collaborations. Publication in journals with refereeing and stimulation of further articles results in a winnowing process that allows the best ideas to emerge.

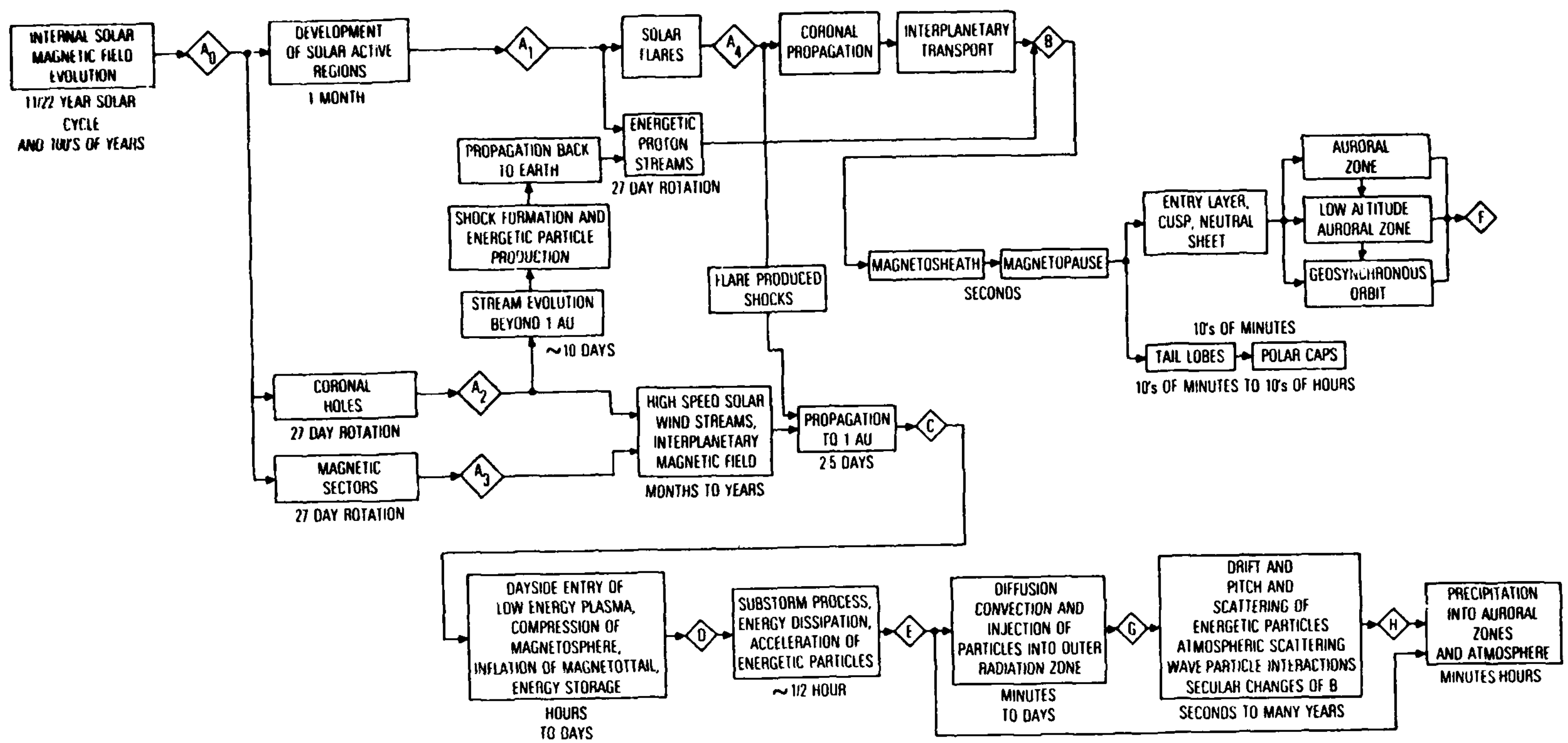
(2) Enhanced Collaborations. We have seen examples of the NASA and the NSF supporting analysis of special periods. This should allow the maximum number of people to participate and may allow certain groups to interact which might not have come together otherwise. New computerized technology has been used to facilitate comparisons of such special data sets.

(3) Simulated Prediction Schemes. Special events and computerized techniques developed in processes like (2) above could be used to test particular techniques.

(4) Field Tests. Particular techniques could be used by space disturbance forecasting centers as trials. Results could be used to refine the techniques.

Table 1. Methods of Testing and Evaluating Predictions.

	Pro	Con
Tradition Collaboration	Well established, comfortable	Slow process, not all data comparisons may be covered
Enhanced Collaborations	Geared to particular goal, new computerized techniques	Hardware limited, requires much individual time, few special events which may not be the critical cases
Simulation	Relatively cheap	Hardware limited, lacks subtleties of field situation, may lack realism.
Field Tests	Allows operating forecast center personnel hands-on experience and interactions with researchers	Very manpower intensive if carried out in real time



LEGEND OF "OBSERVATION POINTS"

A. OPTICAL, RADIO, AND X RAY OBSERVATIONS
B. SPACECRAFT PARTICLE OBSERVATIONS
C. PREDICTION TECHNIQUES BASED ON SOLAR WIND PARAMETERS
D. OBSERVATIONS OF LOW ENERGY ELECTRON ANISOTROPIES, MAGNETIC FIELD
E. PARTICLE INJECTIONS, PLASMA SHEET THINNING, GROUND MAGNETOMETER OBSERVATIONS (Dst, AE)
F. SPACECRAFT PARTICLE OBSERVATIONS, RED ARCS, OPTICAL AND X RAY IMAGING OF AURORAL ZONE
G. SPACECRAFT PARTICLE OBSERVATIONS AND MODEL CALCULATIONS
H. OBSERVATIONS OF ELECTRON ANISOTROPIES AND FLUXES

A_0 SUNSPOT AND GENERAL SOLAR ACTIVITY OBSERVATIONS
A_1 SOLAR OBSERVATIONS AT RADIO FREQ SOLAR MAGNETOGRAMS
A_2 X RAY AND UV SOLAR OBSERVATIONS
A_3 OPTICAL MAGNETOGRAMS OF THE SUN AND CORONAL OBSERVATIONS
A_4 OPTICAL, RADIO AND X RAY OBSERVATIONS OF FLARES

Fig. 1

APPENDIX II

Long Term Magnetospheric Particle Variations (1 Day $< T < \infty$)

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Introduction

The practical importance of studying the variations of energetic magnetospheric particles with durations in excess of 1 day lies mainly in being able to predict, for example, the effect of damage to spacecraft systems or long-term effects on the earth's ionosphere. Since typical systems, be these spacecraft systems or communication/navigation networks, have lifetimes in the range of 5-10 years, the variations of the near-earth environment over the solar cycle become an important aspect of their design and operation. With significant improvements in technology occurring in the same time interval, it is expected that such systems will continue to be replaced on similar time scales over the next half century. The radiation and plasma environment affects some aspect of engineering design and influences the selection of the orbit for certain space missions. With the total budgets of all nations for spacecraft systems and instruments being in the (several) billion dollar range annually, measures costing a few tens of million dollars might be considered quite cost effective.

From the scientific standpoint interest in long term variations of the radiation in nearby space ranges from the considerations of the evolution of life on the planet, where geomagnetic field reversals on geological time scales may result in significant changes in the radiation environment, to the detailed understanding of magnetospheric processes which can be extended to peculiar astrophysical objects such as pulsars and quasars. The complexity of plasma processes in the solar-terrestrial environment has been summarized in Appendix I and it has been shown that most phenomena operate in the time domain between one minute and one day. Consequently, it is necessary for us to logically impose a low pass filter with a cutoff frequency around one $(\text{day})^{-1}$ to address our assigned topic; this is not an easy task. However, we will attempt to do this by adopting the viewpoint that such variations are either adiabatic (as concerns the motion of trapped particles), or the statistical results of non-adiabatic processes such as acceleration and, radial and pitch angle diffusion.

Long Term Energetic Particle Processes

Appendix I contains a comprehensive flow diagram of solar-terrestrial processes with observation points necessary for predictions and, hence, for understanding the phenomena (Figure 1 of Appendix I). The time scales relevant to the consideration of long-term particle variations are also indicated there.

The recognition of the variation of solar activity from one solar cycle to the next and the consequent variability of geophysical effects is manifest by the difficulties which were encountered in predicting the date of Skylab re-entry well in advance. Although sunspot numbers dating back to Galileo in the

early 1600's are available (including such anomalous periods as the Maunder miminum), it is still not possible to accurately predict the level of solar activity in a given solar cycle although the general variations can be predicted. The investigation of the Maunder minimum by such techniques as C^{14} dating is near the extreme upper limit of quantitative study of long term radiation variability. On a shorter time scale, for example, we know that the persistence of active solar regions, which exhibit some periodicity around 45 days should also be included since it is suggested that such periodicities may be present in the energetic electron fluxes obtained in geostationary orbits over the past decade. Twenty-seven day running averages for this data show approximately 8 peaks per year and detailed correlations should be performed.

Recent studies of the interplanetary magnetic field for the period 1963-1976 has shown that the generation of shock structures is more prevalent during active periods. The character of the IMF and of long lived solar wind streams shows variations in the range of years. Consequently particle propagation from the sun also can be affected by the changes. The characteristics of the magnetosphere are also clearly affected by the long-term changes in interplanetary conditions. In addition to large scale erosion events, which are apparent when a large interplanetary shock strikes the magnetopause, there is recent evidence for patchy reconnection between the interplanetary magnetic field and the terrestrial field at the magnetopause. Thus buildup of the magnetospheric energy may occur by global as well as local processes. Thus it also seems plausible that de-excitation of the magnetosphere can occur in the same way, i.e., particle energization may be produced both impulsively and quiescently. We speculate that the "fireball event" in the magnetotail may be evidence of localized, patchy de-excitation and expect the particles from such acceleration events to show up on the outer magnetosphere in a less conspicuous manner than the large scale substorm injection processes, which may result from a neutral point formation across large regions of the geomagnetic tail. If one adopts this point of view, then there is evidence for de-excitation over the period of 10's of days and the magnetosphere may be capable of maintaining a stressed geomagnetic tail for these periods. This approach may be useful in organizing our view of magnetospheric dynamics since it offers a way of viewing the observed outer zone time behavior that brings some order to a very complex pattern.

The energetic outer zone particles, particularly electrons, exhibit large impulsive changes following the injection of accelerated plasma sheet particles into the trapping region. Although there are, on occasion, rapid (less than 1 day) changes, the general pattern is one of exponential decay with time constants in the range from days to 10's of days. Super-imposed on this are smaller injection events, which if not distinguishable, tend to make one believe the decay behavior has been altered. Studies of the decay constants indicate that they do not vary from event to event at a given L value and energy and the decay seems to be consistent with (but not in complete agreement with present calculations) whistler mode wave-particle interactions that result in pitch angle diffusion of the particles down the field line to be lost in the atmosphere. There are periods of time when these outer zone particles show a leveling off of the fluxes for days to 10's of days at a time. There is no reason to assume that the loss mechanisms become inoperative at this time, so we suppose a constant injection is occurring in a non-impulsive way. This

could occur from the integrated injections from a number of fireball or small de-excitation events.

Studies of outer zone electrons have revealed that following the arrival of fast solar wind streams, the fluxes rise within 1-2 days but then decay in a non-predictable manner independent of solar wind conditions. We view this decay as further evidence that the magnetotail is de-exciting itself over the period of some 20-30 days in small scale injection events. The observations of electrons below 4 MeV show variability on the time scale of a year or two at geostationary orbits. However, at lower energies, averages of fluxes from 6 months to a year are consistent with there being no changes in the electron population over these periods in most of the outer zone down to L=4.5. Although definitive long term studies of protons have not been conducted, there is nothing to indicate their long term picture is different than electrons. Short term variations of protons including injection and decay have been studied. In the region between L=2.0 and 4.5, there are differences in the electron multi-month averages that can be as high as a factor of 10. Athough the present quantitative models for trapped electrons attribute these changes to solar cycle effects, it is not clear that the observed periodicities support this conclusion.

An examination of the increases in energetic electrons in the outer zone following magnetic substorms has shown on some occasions time constants that exceed a day, particularly for the lower altitudes. Although some unknown long term acceleration deep within the magnetosphere has sometimes been attributed to cause these effects, it is much more likely that one is seeing the adiabatic transport of previously accelerated particles; this transport is due to the variation of the ring current. In the inner zone, one always finds rises greater than one day which are due to radial diffusion of the particles injected into the outer trapping region.

Starfish and other nuclear detonations provided a large perturbation in inner zone and slot electron fluxes that has allowed very good determinations of the loss rates due to atmospheric scattering and other factors. These exponential decay times were observed to be energy dependent with the longest times being about 370 days around L= 1.45 and energies around 1.0 MeV. Present quantitative electron models of the inner zone no longer contain a Starfish component since this residue has decayed below natural levels.

In the region around L=2.0 energetic protons are known to have exhibited rapid non-adiabatic changes in association with large magnetic substorms. The subsequent recoveries are by radial diffusion. These types of events seem to reflect a slight re-distribution of particles rather than the impulsive injection of new particles. For the existing proton models the variations due to redistributions or long term variations are small enough (factors of $\approx$ 2 in restricted regions of space) that they have been ignored and the models are static except at low altitudes. Here the calculated predictions in 1964 that energetic proton fluxes would vary with the solar cycle have been confirmed and enough low altitude measurements were taken in various time periods to provide a somewhat quantitative description. Since these changes are produced by density increases in the upper atmosphere which in turn are caused by solar EUV emission that is dependent on coronal hole formation, the predictive aspects of

this phenomena are not without difficulty.

Finally we should note that changes in the internal geomagnetic field can produce long term changes in the energetic particle fluxes. Current internal field models possess secular changes to the dipole moment that indicate significant changes in times approaching 1000 years. The adiabatic changes due to this effect have been calculated. Further, the well known dipole reversals that occur on geological time scales may result in the complete disappearance of the magnetospheric cavity and the solar wind interaction would occur with the ionosphere as it does at Mars.

Prediction Techniques

Prediction techniques for energetic particles within the magnetosphere depend on two kinds of knowledge. The first is the spatial variation of the trapped fluxes as determined by performing averages over at least several months at each point available for observation. Because the magnetospheric cavity itself undulates, changes shape, and moves in toto with respect to any preselected coordinate system, the separation of time effects, the second type of necessary knowledge, from spatial effects is never an easy task. However imperfect the situation may be, one proceeds by establishing some quantitative description of particle fluxes that to first order represents the average situation that any spacecraft would encounter in its flight profile. In a real orbit the time variations seen in executing each revolution may be as much as five or six orders of magnitude even using these static or quasi-static models. Added to this picture as a modulating influence are the inherent time variations themselves. The rapid departures from this quasi-equilibrium, which are represented by all the phenomena discussed in Appendix I, are spoken to separately within the phenomenology of the event in question. This is somewhat similar to conditional probability in that once an event has occurred, one can address some average properties of the event. For time variations that are long with respect to the multi-month averages constructed to obtain a spatial distribution, their cause is generally attributed to influences outside the system itself. Consequently, effects which show changes from years to several hundred years are believed to be due to solar processes or to transport processes between the sun and the earth. Processes that range from thousand years to several million years are associated with the internal dynamics of the earth such as the currents that produce the internal field. The time domain between 1 and 60 days is perhaps the most fruitful one for the magnetospheric scientist to study since the loss processes of most of the particles and the small scale de-excitations of the cavity lie mainly within this range.

The improvement of predictive techniques in this area is dependent on two things. First, more simultaneous observations of particle measurements are needed to obtain better spatial distributions. Not only are more spacecraft needed to perform these measurements but methods for providing the data collected to some centralized data base so it can be used effectively for producing models is needed. The use of Coordinated Data Analysis Workshops might be a way of improving the data bases needed for particle modeling and also bring into the modeling arena some of the experimenters involved in the original measurements. Unless there are major improvements in the numbers and types of instruments flown for these purposes, any enhancement in the collection of such

data coupled with added emphasis on the need for such studies represent the only pragmatic approach for improving the situation.

Since the motion of the energetic particles is governed by the magnetic field, the improvement of these models to cover disturbed conditions and the relaxation back to quiet conditions will be important element in improving the understanding of particle transport and decay. It is mainly through the magnetic topology of the geomagnetic tail that one can determine the energy stored in the tail. Knowing this quantity as a function of time, even crudely, would be a necessary parameter to testing the concept that de-excitation of the cavity by the acceleration of particles in patchy regions contributes to energetic particles in the outer trapping region.

Inputs from Other Working Groups

It is apparent from the discussion given in the previous section that inputs from the Working Groups on Interplanetary-Magnetosphere Interactions and Geomagnetic Disturbance Predictions concerning magnetic field models, magnetic energy stored in the tail, magnetic monitoring measurements in the geostationary orbit and at certain ground-based stations are the most important elements to study the configuration of particles in an adiabatic sense, once the non-adiabatic effects have occurred in the magnetosphere. Projects to concentrate on the change of energetic particle populations during certain events, particularly substorms, are fostered by coordinated measurements, as has become highly developed during the International Magnetospheric Study. Predictions of possible magnetospheric events from solar events have also proved useful to satellite measurements in the past. If the data from ISEE 3 could be made available in real time to a prediction center, then alerts for interplanetary shock waves and other solar generated disturbances could be used to improve data coverage prior to and during the magnetospheric response to such events.

Testing and Evaluation of Predictions

The understanding of a process improves the ability to predict. Even a statistical understanding, as opposed to a physical one, provides a statistical prediction. The latter techniques are used very extensively in doing predictions on solar events since the complexity of the processes are indeed very great. The general methods of evaluation have been provided in Appendix I. The specific viewpoint we have taken in this position paper is certainly one that is subject to test. Can all of the long term decay processes displayed by magnetospheric particles be shown to be governed just by internal processes? The effect of magnetospheric events seems to result in a general increase of the particle population save for a few isolated regions where non-adiabatic transport might result in a catastrophic increase in loss rates. It is felt that enhanced collaborations, particularly through Coordinated Data Analysis Workshops as well as traditional methods will be the most fruitful in evaluating the new prediction techniques which may become available through an increased study of decay processes and their relationship to the energy content of the various regions of the magnetosphere.

LABORATORY OPERATIONS

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Space Sciences Laboratory: Atmospheric and ionospheric physics, radiation from the atmosphere, density and composition of the atmosphere, aurorae and airglow; magnetospheric physics, cosmic rays, generation and propagation of plasma waves in the magnetosphere; solar physics, studies of solar magnetic fields; space astronomy, x-ray astronomy; the effects of nuclear explosions, magnetic storms, and solar activity on the earth's atmosphere, ionosphere, and magnetosphere; the effects of optical, electromagnetic, and particulate radiations in space on space systems.

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